Third Annual IGCP 565 Workshop: Separating hydrological and tectonic signals in geodetic observations

October 11-13, 2010, Reno, Nevada, USA

The third annual workshop of the International Geoscience Programme Project 565 "Developing the Global Geodetic Observing System into a Monitoring System for the Global Water Cycle," which was jointly organized by IGCP 565, the Group on Earth Observations (GEO) and the Global Geodetic Observing System (GGOS), was held on October 11-13, 2010 at the University of Nevada, Reno, in Reno, Nevada, USA. During the three days, a total of 57 participants from elven countries in four continents discussed the status, science challenges and approach to addressing the challenge of utilizing geodetic observations for the monitoring of changes in terrestrial water storage.

More than one billion people are today without access to sufficient clean and healthy drinking water, and this number is likely to increase dramatically over the next decades. As pointed out by the 2006 Water Report of the United Nations, this is not so much a problem of abundance but rather of insufficient governance. Responsible regional water management will be essential for satisfying the demand for drinking water. Currently, regional water management is hampered by a lack of sufficient observations of the surface and subsurface terrestrial water storage. A much improved observation system providing information on all reservoirs of the water cycle on regional to local scales is needed, if we want to avoid severe human and ecological disasters cause by inappropriate water management.

The goal of the IGCP 565 Project is to utilize the global geodetic observing infrastructure for the monitoring of mass transport in the water cycle, particularly on regional scales. Geodetic observations of the changes in time in Earth's gravity field, shape, and rotation capture the signals of redistribution of water mass on the globe. The dramatically increased accuracy of the geodetic techniques over the last four decades carries a great potential for measuring water mass as it cycles from one reservoir to another. With a series of five annual workshops and a number of associated research projects, IGCP 565 explores this potential and aims to provide useful products to regional water management, particularly in developing countries.

The series of five annual workshops aims to facilitate coordination of the research and capacity building within the framework of the IGCP 565 Project. The first workshop in 2008 reviewed the current status of research and technology with respect to the extraction of hydrologic signals from geodetic observations and identified current gaps, challenges and obstacles. The second workshop in 2009 focused on future satellite gravity missions, which are a core element in a geodetic observing system for the water cycle. The next two workshops in 2011 and 2012 will be devoted to hydrologic applications, particularly in developing countries, and they will bring in end users from the wide area of regional water management.

Figure 1: Group Picture taken on the 3rd day of the Workshop.

The focus of the 3rd IGCP 565 Workshop was on the separation of hydrologic and tectonic signals in geodetic observations of time variable Earth's gravity field, surface displacements, and rotation. In regions like the Southwestern U.S., the Mediterranean, Northern India, East Africa, and large parts of East Asia, tectonic processes and changes in land water storage produce overlapping signals in geodetic observations. At the same time, these regions experience water scarcity and would benefit from improved water management informed by improved data on water storage changes. In order to fully utilize the potential of geodetic observations to provide estimates of terrestrial water storage changes in these regions, the tectonic and hydrologic signals need to be separated. In other regions, geodetic signals of present-day changes in water storage are superimposed by contributions from large past changes in glaciers, ice sheets and large lakes hampering the use of geodetic observations as constraints to current climate change impacts.

The 3rd Workshop brought together experts in the relevant fields including geodesy, tectonics, and hydrology for a review of the current state of knowledge with respect to the geodetic fingerprints of the tectonic and hydrologic processes. The goal was to identify the main challenges in modeling and separation of the various contributions, and to make progress towards an agenda to address these challenges through focused research projects.

During the first day, a series of invited keynote presentations set the stage for four breakout sessions on the second day. The third day was devoted to a synthesis of the results from the breakout sessions and the development of a perspective for actions that would lead to improved applicability of geodetic observations for hydrologic and global change studies and better informed decision making.

In the first plenary session titled "Hydrology, Tectonics, and Geodesy: Status and Challenges", Peter Clarke addressed the problem of observing the hydrosphere and solid Earth together. The challenge arises from the fact that many processes in the Earth system impact geodetic observations on sub-daily to secular time scales and on sub-kilometer to global spatial scales. As illustrated in Figure 2, on the solid earth side these processes include volcanic and geothermal activities, post-seismic deformation, response to surface loading, plate boundary deformation, and global geodynamics. In the fluid envelope of the solid Earth, all mass redistribution in atmosphere, oceans, land water storage, and the cryosphere need to be considered. He analyzed the complicated challenge of separating the signals of hydrologic mass movements and tectonic signals in geodetic observations. Discussing the wide range of temporal and spatial scales covered by these two major Earth system processes as compared to the available observational technologies and infrastructure, he arrived at three key questions to be addressed during the workshop:

- How can we bridge the gap in spatial scales between regional to global measurements and point to catchment measurements?
- How can we isolate the long-term hydrologic changes from secular effects due to tectonics, post-glacial rebound, and similar solid Earth processes?
- How can we improve measurement accuracy and robustness to seasonal and other artifacts?

These questions guided the discussions throughout the workshop.

Gerald Bawden showed that observations of geodetic techniques with high temporal resolution (such as the Global Positioning System, GPS) and high spatial resolution (such as Interferometric Synthetic Aperture Radar, InSAR) can be combined to provide a picture of Earth's surface displacements with high spatial and temporal resolution. However, hydrologic interpretation of these observations requires joint consideration of both hydrology and tectonics. For example, for volcanic and tectonic studies, it is important to avoid margins of basins, as these are likely to be affected by hydrologic effects. Steady-state anthropogenic signals associated with water usage also have the potential to mask the deformation signal arising from tectonic processes.

Kosuke Heki considered the rotational signal of large earthquakes and concluded that for the earthquakes that occurred during the last century, only the 1960 Chilean earthquake induced a rotational signal large enough to be detected given today's accuracy of observations of changes in Earth's rotation. Xiaoping Wu showed that a combination of geodetic observations of surface displacement, gravity field variations, and rotational changes provides a basis for an inversion of mass transports in the water cycle. However, he identified several error sources in the geodetic data that need to be addressed in order to improve the inversion result, including a potential GPS Draconitic Harmonic error at a period of 351 days, which biases the seasonal signal.

The second plenary session titled "Transient Tectonic and Hydrological Signals" gave an overview of the current knowledge about the order of the signals at various spatial and temporal scales. The Gravity Recovery and Climate Experiment (GRACE) has provided new insight into mass transport in the water cycle from large river basin to global scale. Jianli Chen commented on the low spatial resolution of GRACE, which results in some spatial leakage of signals. Paired with residual errors in the GRACE gravity model, the available inversions have uncertainties comparable or larger than predictions based on forward modeling using the output of meteorological and land data assimilation models.

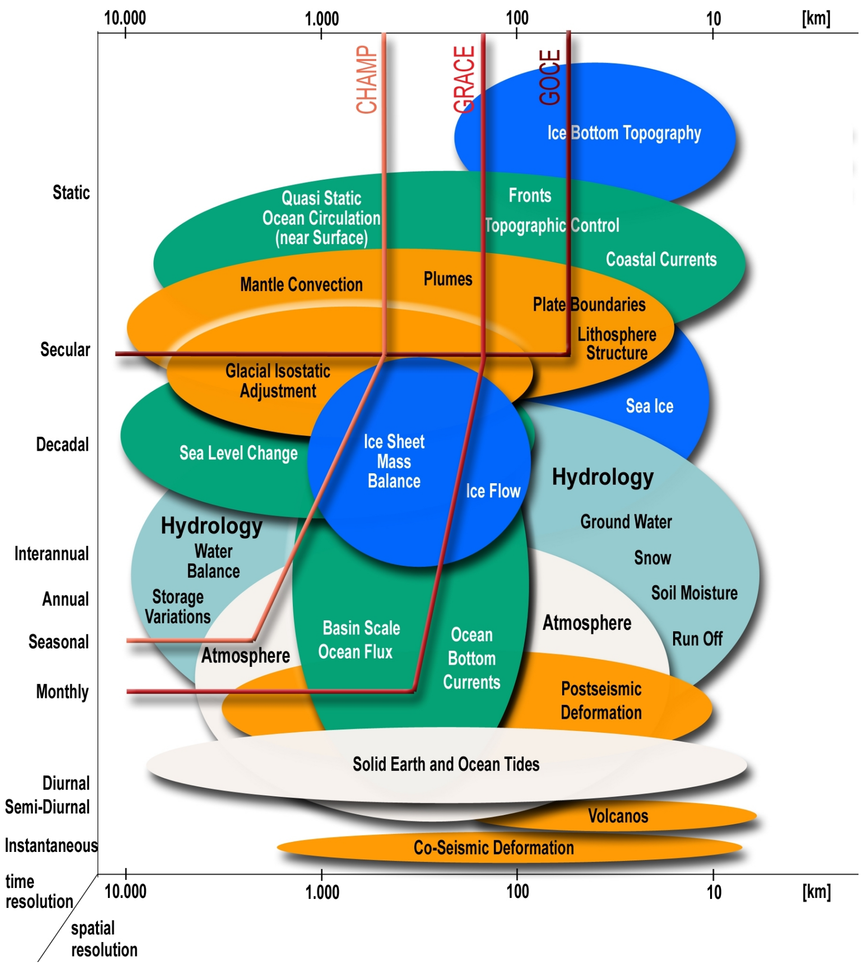

Figure 2. Geodetic observations carry signals of a wide range of processes in the solid Earth and its fluid envelope. The geodetic fingerprints of these processes have temporal time scales from instantaneous to secular, and spatial time scales from local point movements to global. The figure illustrates the spatial and temporal scales for gravity, and a similar figure applies to surface displacements as well. From Ilk et al. (2005).

Evelyn Roeloffs used several transient strain events occurring in the Southern United States to consider the role of fluids in these events and concluded that strain transients may be responses to subsurface fluid pressure changes, but could not rule out the possibility that these fluid pressure changes could also be caused by deformation.

Two case studies presented during the third plenary session focused on the Southwestern U.S. and Eastern Africa, i.e., regions where significant tectonic and hydrologic signals can be expected to be present in the geodetic observations. The EarthScope Plate Boundary Observatory provides high-quality observations of surface displacements for the Western U.S. Charles Meertens identified the signals of the recent droughts in the Southwestern U.S. in these observations, and showed that model predictions agree very well with the GPS observations. Considering the seasonal signal, he concluded that stations showing a seasonal signal diverting from the generally smooth spatial amplitude and phase patterns turned out to be affected by local hydrologic processes. Therefore, integration of GPS and InSAR observations would help to better identify what is going on. These analysis results underlined that isolating the signal of mountain building in the geodetic observations, for example, for the Sierra Nevada, requires a thorough understanding of the hydrologic signals. This was confirmed by Danan Dong, who considered the secular velocity field derived from GPS observations. He found that most of the abnormal spots in GPS-observed vertical velocity in California and Nevada are real hydrologic and anthropogenic signals rather than artifact of errors. While hydrologic and tectonic signals are superimposed on each other, the hydrologic signals typically have much smaller spatial scales and occur in isolated areas. Therefore, if these signals are identified and subtracted, the remaining vertical velocity field is likely to better represent the tectonic information. In particular, these results confirm that GPS vertical measurements are very sensitive to hydrologic signals and can therefore provide an effective means to monitor underground fluid variations.

Based on repeated in-situ gravity measurements carried out in the Southwestern U.S., Don Pool discussed the spatial and temporal distributions of gravity changes. The cause of the largest changes of more than 40 μGal depended on the time scales. Rapid changes were found in areas with large periodic input and subsequent drainage over weeks to months, including ephemeral stream channels and porous rocks in high elevations. Large long-term trends occurred in areas with significant groundwater mining and changes from groundwater to surface water irrigation. Smaller changes were seen across broad areas of alluvial basins and locally in areas of low porosity rocks. Norman Miller demonstrated the extreme effect of on-going and predicted climate change on groundwater in the Central Valley of California through model simulations in collaboration with the California Department of Water Resources. In their study, an integrated surface-groundwater model was used to simulate a series of drought conditions lasting from ten to seventy years and with water reductions from 30% to 70% of normal. This future climate analogy was indicative of the likely shifts in relative groundwater for sub-basins within the Central Valley. One of the important findings that results from these simulations was that the northern region, Sacramento Basin, was most likely to be depleted at a slower rate than the southern region, San Joqin and Tuilure Basins. Management for water resource resilience was encouraged, but also application of geodetic signals for monitoring such groundwater variations.

For the second case study, Sarah Stamps gave an overview of GPS geodesy experiments in the East African Rift zone addressing the questions: What are the kinematics of the East African Rift? How is strain distributed across the East African Rift? What is the budget of forces acting to initiate and sustain continental rifting? What is the role of magmatic intrusions in the early stages of rifting? These questions are considered in a number of projects: Tanzania: Kinematic constraints on mantle-lithosphere interactions; Uganda: Structural expressions of extreme rift-flank uplift; Ethiopia: Magma-tectonic processes in an active transitional rift from seismic, GPS, and modeling studies in Afar; Madagascar: Kinematic constraints on the Lwandle-Somalia plate boundary. Elias Lewi reported on a case study in the Borena Zone, Southern Ethiopia, which illustrates the role of high precision geodetic survey in groundwater exploration. He showed that by using a high precession measurement approach, gravity surveys can play a crucial role in groundwater exploration work. As a long-term benefit, the gravity observations can also be used to monitor groundwater extraction. In conjunction with other geophysical observations, the high precision gravity data provides accurate constraints for basement depth and in addition helped to identify regions of high groundwater potential.

On the second day of the Workshop, four breakout session provided ample opportunities for in-depth discussions of the scientific and methodological issues identified in the keynotes presented during the first day. Each of these sessions combined a number of presentations with discussions of the key questions. Reports from these breakout sessions were then presented in a plenary session on the third day.

The breakout session on "Forward modeling of tectonic and hydrologic signals" identified the need for more complex representation of the hydrologic and tectonic signals than the currently widely used harmonic seasonal cycles and linear secular trends, as well as to go beyond the typical approach of studying residual time series without fully understanding the modeled signals that have been removed. The need for access to hydrologic observations was emphasized and the modeling of all loading contributions including those resulting from anthropogenic activities was requested. Combination of the standard geodetic observations with additional sensors (e.g., strainmeters) in an integrated analysis of hydrologic and tectonic processes was recommended. The use of global hydrologic models was recommended for modeling the large-scale hydrologic effects and to separate these from local contributions. For local hydrologic effects, a combination of in-situ gravity and GPS measurements would be very valuable, and these effects often can be modeled using only precipitation (from land-surface rain gauges or satellite derived estimates), or using borehole water level measurements. For the separation of hydrology and tectonics, longer records are needed since hydrologic signals also include long-term variations linked to climate variability (El Nino, global climate changes, etc.). The development of regional-scale hydrology models was recommended in order to separate basin and catchment-scale hydrologic signals from regional-scale tectonic deformation.

The breakout sessions on "Separation of signals on micro to basin scales", "Separating plate tectonics, postglacial rebound and contemporary global change signals", and "Improving the observing system and consistency of fingerprints in surface displacements, gravity and rotation" focused on answering the questions posed in the presentation by Peter Clarke.

Of high importance for a reduction of observational uncertainties is the improvement of the geodetic reference frames, which provide the basis for combining different data sets (such as point observations for GPS and geodetic imaging from InSAR) and models in order to bridge the gap between global to regional spatial scales and very local scales. The development of an improved International Terrestrial Reference Frame (ITRF) requires the densification of the global network of reference stations, a closing of the spatial gaps in this network particularly in Africa and Asia, and a better robustness of the observation networks.

The need for consistency in modeling and evaluating displacement, gravity, and hydrologic processes was emphasized. This includes local station motion, spherical harmonic signal decomposition, and weighting of geodetic parameters. Ground truth networks are needed at a higher density and with quality control protocols that ensure station accuracy.

A consistent modeling framework for the assimilation of observations of temporal variations of gravity, surface displacement and rotation that can make use of data with variable spatial and temporal resolution was considered mandatory in order to fully utilize the benefits of the geodetic observations. Such a modeling framework would allow merging of point to basin-scale observations and integrating new emerging technologies with existing ones. It was emphasized that geodesy is at the intersection of many fields (such as solid Earth science, tectonics, volcanology, hydrology, oceanography, atmospheric science, geotechnics, etc.) and using the geodetic observations requires the modeling of a range of physical processes in all these fields. This creates the need to better understand the physics of these processes and to develop modeling techniques for improved smoothing and filling of gaps in observations. Ultimately, an Earth system approach is needed for the comprehensive analysis of geodetic observations.

A critical point is the fact that model predictions normally are provided without any information on uncertainties. It was emphasized that realistic uncertainties attached to model predictions would facilitate a more robust inversion for signals due to processes not included in the models. Initial estimates of model uncertainties could be obtained from the standard deviation of the predictions of the same parameters by a number of models. For example, a set of global land data assimilation models could be used to estimate the uncertainties in predictions of changes in terrestrial water storage.

The workshop identified hydrogeodesy as an emerging new field, which entails the need to educate hydrologist, other researchers studying various aspects of the water cycle, and water managers how to utilize the tools and methods of this field. To achieve this, the geodetic communities need to increase interactions with other fields, particularly hydrology, and a mutually understood language needs to be developed. The concept of a geodesy web portal focused on the needs of hydrogeodesy was proposed. Such a web portal would give access to relevant products from GRACE, GPS, and InSAR. Currently, no such one-stop portal exists, and hydrologists who want to use geodetic products and relevant models find little support for discovery of the products and their application. The development of such a portal should follow relevant ISO standards in order to ensure interoperability with other data portals.

The importance of capacity building in developing countries was highlighted, and participants were encouraged to provide local assistance for installation of new infrastructure in developing countries. On-going activities such as AFREF and AfricaArray are relevant to hydrogeodesy and support from experts outside of Africa for these networks was recommended.

Addressing the question of how long-term hydrologic changes could be separated from secular tectonic effects, the need for long and homogeneous records emerged as a central requirement. Promoting long-term operation of observation networks, as well as uninterupted series of satellite missions (with follow-on missions for on-going and planned mission such as GRACE, ICESat, and DESDynI) was encouraged. Sufficient funding for the sustainable operation of observation networks emerged as a crucial precondition for the development of hydrogeodesy as a tool for regional water management. Geodetic data processing and analysis methods are in constant development. Therefore, access to older data sets for the purpose of reanalysis is needed in order to create long and homogeneous time series. Data sharing is important for increased spatial and temporal coverage. Increased and easy data sharing is a main goal of GEO, and it was recommended to use the GEO Portal for data discovery and to bring the needs of hydrogeodesy to the attention of GEO. An avenue for that could be the publishing of observational requirements as well as the user types and applications benefiting from hydrogeodesy in the User Requirement Registry developed by GEO.

On decadal to multi-decadal time scales, hydrologic signals are not truly secular. Therefore, the use of predictions from hydrologic models calibrated by geodetic observations was considered as an appropriate means to separate these effects from the truly secular tectonic signals associated with, for example, postglacial rebound and plate tectonics. The ratio of signals in gravity to those in vertical displacement helps to identify the origin of mass changes. Different spatial and temporal signatures of the hydrologic and tectonic signals in the vertical and horizontal components of surface displacements provide further indications of the source processes causing the observed displacements. The combination and comparison of different techniques (such as GRACE, GPS, LIDAR) can leverage the strength of multiple data types and make use of the fact that hydrologic and tectonic signals are different in these techniques.

The discussion of the question of how measurement accuracy and robustness to seasonal and other artifacts can be increased further underlined the need to combine different techniques. Improved understanding of loading due to atmosphere, cryosphere, terrestrial hydrosphere and ocean would lead to better models for surface displacements and gravity changes caused by these processes. For the cryosphere, improved models for Antarctica and Greenland were mentioned as priorities. Comprehensive ocean monitoring would be essential for better constraints on the global mass balance in the water cycle. Consistency of data analysis and modeling was identified as an important issue currently not sufficiently addressed. Many of the geodetic data have artifacts due to changes in equipment, data processing and modeling. It was recommended to catalog these artifacts and to implement meta data standards that would make this information easily accessible.

Considering the relevance of geodetic infrastructure for many societal applications, including geohazards mapping and monitoring, meteorological and climatological applications, space weather monitoring and prediction, and disaster assessment and response, it was recommended to exploit this multi-purpose aspect of the infrastructure for the promotion of long-term funding for geodetic infrastructure with the goal of building reliable and resilient services. In order to promote hydrogeodesy, it was recommended to identify and publicize a demonstration pilot project that shows the utility of hydrogeodesy for regional water management.

Subsequent to the reports from the breakout sessions, a plenary session summarized the science and observational challenges identified during the workshop. John LaBrecque presented the plans of NASA and showed that these plans fully respond to the relevance of the geodetic reference frame and geodetic observations for research related to tectonics, geohazards, and hydrogeodesy. Geoff Blewitt gave an overview of a recent study by the National Research Council on the national geodetic infrastructure in the USA, which also underlined the importance of a sustainable operation of sufficient geodetic infrastructure in support of research related to many pressing societal needs.

In summary, the presentations and discussion at the workshop made very clear that there is considerable added value in applying geodesy to support hydrologic cycle modeling and monitoring, especially for terrestrial water storage. However, there remain challenges in the uncertainties of observations, data analysis, forward modeling, inversion, and synthesis of geodetic products, which need to be addressed in the development of hydrogeodesy as a science field with a high potential to help address the world's water problems. Questions on the suitability of geodesy signals for hydrologic applications hinge on the variability of the signal within different timescales from months, seasons, to decades. Geodetic forward modeling requires quantification of the hydrologic loading, which can be modeled as a global signal. The determination of the global mass balance, however, remains an issue, especially if local hydrologic variations are to be determined. Model errors will continue to propagate through such calculations, requiring new methods of error reduction for improved predictive capability. Tectonic challenges include exploring different rheological models and quantifying the error budget.

Two primary recommendations that are outcomes of the workshop are: (1) Capacity building with application of geodetic products that water resource decision makers are able to readily access and easily use, and (2) development of a demonstration project in California that merges geodetic information with hydrologic modeling via assimilation and leads to realistic technology transfer to African nations through a similar project in the Nile Basin.

It was proposed that an initial pilot demonstration projects in California will demonstrate the utility of hydrogeodesy, as it is a region rich in groundwater and surface water observations. There is already a collaboration with the California Department of Water Resources. GRACE-derived terrestrial water storage variations for the period 2002-2009 have been calculated for the California Central Valley, a region where more than half of the US fruits and vegetables are grown, and there is currently State agency (CWDR) interest in GRACE and hydrogeodesy applications. A key question is whether the approach applied to California will also apply in regions of Africa, and whether such a pilot can bring together the ongoing activities in Africa needed to build a pilot project that links science to water resource decision makers in Africa. The advantage of the Nile River basin is that there are no significant signals from postglacial rebound that would impact the geodetic signal analysis. Such a pilot should have region-specific issues that bring stakeholders and water managers into such an activity. It is suggested that the Africa pilot should involve the World Bank, USAID, UN Habitat, UNESCO IHP, WaterNet, NASA, and other groups already working in the Nile basin. The science contribution will require development of tools for end users, provide advice for infrastructure, and capacity building for operational activities. This will require international participation from African countries within the Nile basin and data sharing through a common decision support framework.

For a full documentation of IGCP 565 and the workshop series, see http://www.igcp565.org.

Hans-Peter Plag
Nevada Bureau of Mines and Geology
University of Nevada, Reno
Co-Leader of IGCP 565

Norman Miller
Earth Sciences Division, Berkeley National Laboratory and
University of California at Berkeley
Co-Leader of IGCP 565